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ATMOSPHERIC CONSIDERATIONS FOR SKIPPING SPACEPLANE TRAJECTORIES

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Abstract

A mission to release a payload to low polar earth orbit by a conceptual Reusable Aero Space Vehicle (RASV) is considered for Monte Carlo atmospheric conditions. Atmospheres are applied to a baseline trajectory in which, after payload release, the spaceplane circumnavigates the globe and returns to its launch site by a boost glide maneuver (i.e. by skipping off the atmosphere) and the payload employs a small attached booster to put a satellite into a final orbit. Around-the-world RASV trajectories are found to be feasible under many atmospheric conditions; however, trajectory characteristics are found to vary substantially with atmospheric variations when a given set of fixed flight controls are used.

INTRODUCTION

This analysis simulates the effects of varying atmospheric conditions (including winds) upon the performance of a spaceplane that attempts to fly an around-the-world mission from within the continental United States, en route releasing a payload into prescribed near-orbit conditions. In order to reduce the influence of the earth's rotation and to more accurately assess the influence of latitudinal climate differences, a trajectory that approximately crosses the earth's poles is assumed. The purpose here is to determine whether a smaller, cheaper vehicle than is required for orbital maneuvers can effectively deploy satellites.

Flight simulations have been generated by combining existing software to model trajectories with software to simulate random atmospheres. Specifically, the Program to Optimize Simulated Trajectories, POST Version 5.1 (Brauer 1990), developed by Martin Marietta Corporation, has been combined with the NASA/MSFC Global Reference Atmospheric Model - 1995 Version, GRAM-95 (Justus et al.1995). Both programs have been modified to reduce execution time and so that GRAM-95 can be called as a subroutine by the POST program. The specifications of a sub-orbital version of a Reusable Aero Space Vehicle (RASV) as envisioned by Boeing Corp. (Froning 1996) prescribe the spaceplane model parameters for POST.

THE ATMOSPHERE MODEL

The GRAM-95 computer code was chosen to provide atmospheric data because it is a standard program that can provide geographically and time varying, correlated, random values of necessary parameters. It computes data in the lower (0-27 km), middle (20-120 km), and upper (90+ km) altitudes via three different models and obtains results at transition altitudes by "fairing" estimates of the individual models. Temperature, density, pressure, speed of sound, and wind components are needed for POST calculations.

The middle atmosphere model in GRAM-95 is based on data from the Middle Atmosphere Program, MAP (Barnett and Corney 1985a and 1985b) and provides the most critical data for skipping trajectories to POST from the vehicle altitude and latitude, the elapsed time, and the month of the year. Diurnal effects are not modeled; nor are solar effects, nor gravity waves.

The upper and lower portions of the atmosphere have a smaller influence upon spaceplane performance since little time is spent at these altitudes. It is useful to understand, however, that (i) in the lower atmosphere the Global Upper Air Climatic Atlas, GUACA Version 1.0 (Ruth, et al. 1993), provides historical data from which random parameters are obtained, and (ii) in the upper atmosphere model, or Jacchia model (Hickey 1988a, and 1988b), influences of the day of the month, diurnal variations, and solar effects (as well as altitude, latitude, time elapsed, and month) are taken into account.

THE BASELINE TRAJECTORY (1962 U.S. STANDARD ATMOSPHERE USED)

A baseline trajectory was generated for a flight of the RASV from Edwards Air Force Base, California, around the world and back, by two POST runs using a polar trajectory headed initially due south, through a geographically uniform U.S. Standard Atmosphere, 1962 (with no winds).

In the first run of the baseline case POST was requested to maximize the weight of a payload subject to prescribed conditions at the end of the powered phase of ascent:

(i) inertial flight path angle must be within 0.001° of 0.0°,
(ii) inertial velocity is required to be within 3.05 m/sec of 7868 m/sec, and
(iii) altitude must lie within 30.5 m of 103,783 m (104 km).

These conditions occurred just prior to an unpowered elliptical orbit (Hohmann) transfer to an apogee altitude at which the payload could be released. The vehicle assumed a horizontal lift-off position, was sled-launched at an azimuth of 180° (due south) with an initial relative velocity of 183 m/sec from a runway at 694 m altitude, and was powered by two modified space shuttle main engines (SSMEs) for 522.31 seconds thereafter. The engines were assumed to initially deliver 4.49 million N of thrust, have an instantaneous specific impulse (ISP) of 449.8 sec and an exit area of 5.39 m^2. When the RASV reached 15,240 m, its extendable nozzles were moved to a second position so that 4.63 million N of thrust was delivered with an ISP of 463.5 seconds and an exit area of 16.16 m^2. The propellant weight decreased from an initial weight of 494,742 kg and the vehicle dry weight was 60,918 kg (not including a payload of about 11,340 kg) for a gross takeoff weight of about 567,000 kg. Drag and lift calculations used a reference area of 527 m^2 and RASV drag and lift coefficients. POST determined that a payload of 11,385 kg could be lifted the attack angles shown in Table 1 were employed (with bank angle zero).

TABLE 1. Attack and Bank Angles for RASV Ascent.

Event	Time (sec)	Attack Angle (deg)
1	0	3.569
2	15	6.917
3	35	2.440
4	75	1.098
5	175	2.165
6	295	1.684
7	345	0.811
8	395	0.713
9	445	0.232

These attack angles and payload weight were inserted into a second POST computation in which the RASV was required to return to Edwards AFB from the payload release point without releasing its payload. (It was assumed that a return with the payload would be more difficult than a return after a release). The aerodynamic heat rate was constrained to a maximum of 2524 kW•sec/m^2 - based upon a 0.3048 m reference sphere. POST was used to meet these objectives by choosing an angle of attack and a bank angle during each of the phases: (i) from vehicle apogee

until 311,374 N of lift was generated, and (ii) from this point until the vehicle relative velocity dropped to 1,524 meters per second. From this point the RASV was (somewhat unrealistically) assumed to dive at a constant flight path angular rate for landing. A skipping return to Edwards AFB was found to be possible using attack angles of 6.704° and 6.771° with corresponding bank angles of -12.82° and -12.91° for the two phases, respectively. The baseline ground track (subvehicle path) appears in Fig. 1 and the associated altitude verses time profile is given in Fig. 2.

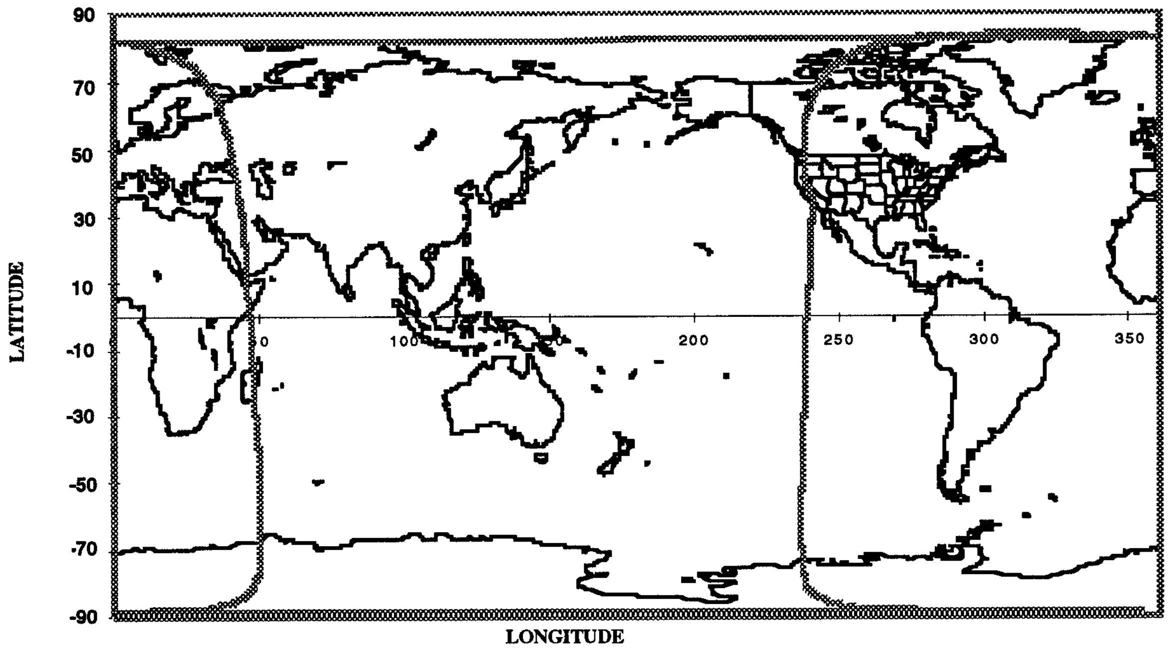

FIGURE 1. Ground Track for the Baseline RASV Skipping Trajectory.

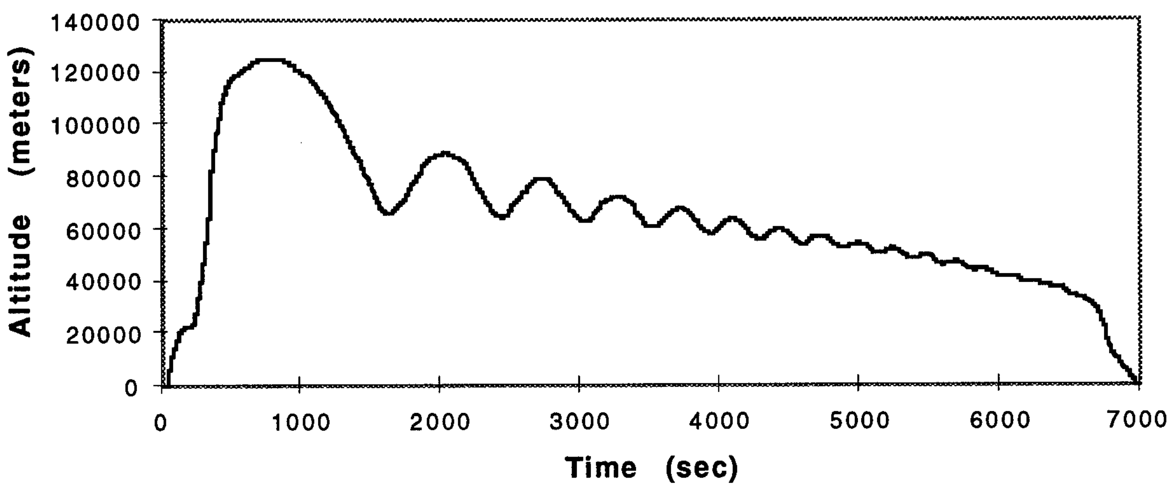

FIGURE 2. Global Skipping Profile for the Baseline RASV Trajectory.

.<u>Monte Carlo Flight Simulations</u>

From the optimized (i.e., baseline) trajectory for the uniform atmosphere, it was possible to execute Monte Carlo POST runs with GRAM-95 generated, globally varying, random atmospheres by implementing the attack angles, bank angles, and payload weight of the baseline trajectory. Twenty such runs for each of January, April, July, and

October were performed on a 200 MHz Pentium-class PC, and required approximately 2 minutes each using POST's projected gradient optimization mode with zero control vector iterations.

Since GRAM-95 requires that parameters for solar activity be input (for effects above 90 km) in each run, random solar parameters were generated externally. The 3-hourly geomagnetic index a_p (used in the GRAM model to compute a geomagnetic correlation to the exospheric temperature) was selected from historical percent frequency distribution data. The daily and mean 162-day average values for the solar 10.7-cm radio noise flux were assumed to be equal and had a value selected randomly by use of the uniform distribution U[40,240]. The 15th day of the month and a Greenwich mean time (UTC) of 1:00 were used for all runs - these only influence GRAM-95 output above 90 km. Diurnal variations at middle and lower altitudes could not be simulated.

Since Monte Carlo runs were not subjected to the restrictions of the baseline run, but merely used the same payload, bank angles, and attack angles, landing location varied. One October run failed to meet the 311,374 N of lift baseline phase criterion, so phasing was implemented at 291,330 N for that run; however, all other runs completed normally.

The peak altitudes of the trajectories averaged 129,613 m for January, 143,473 m for April, 147,757 m for October, and 180,992 m for July. Vehicle peak heat rate was higher for the higher flights (averaging, in kW•sec/m^2, 2708 for January, 3135 for April, 3178 for April, and 3921 for July); however, total aerodynamic heating was lower for these paths. The situation is illustrated in Fig. 3, Fig. 4, and Fig. 5 for the case of an especially high July flight and an especially low January flight. Confidence intervals for peak altitude and peak heat rate in each set of 20 runs are given in Tables 2 and 3.

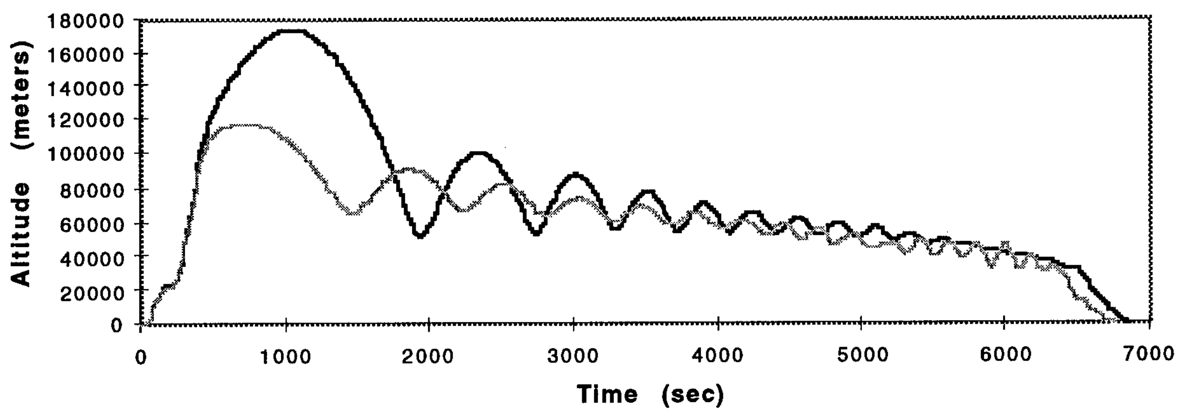

FIGURE 3. Altitude Profiles for a Low January Flight and a High July Flight .

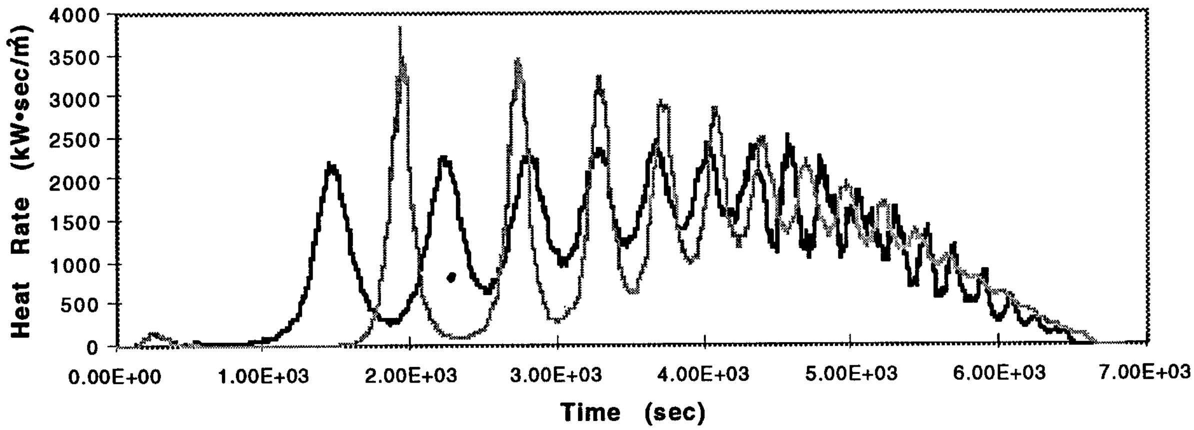

FIGURE 4. Heat Rate for a Low January Flight and a High July Flight

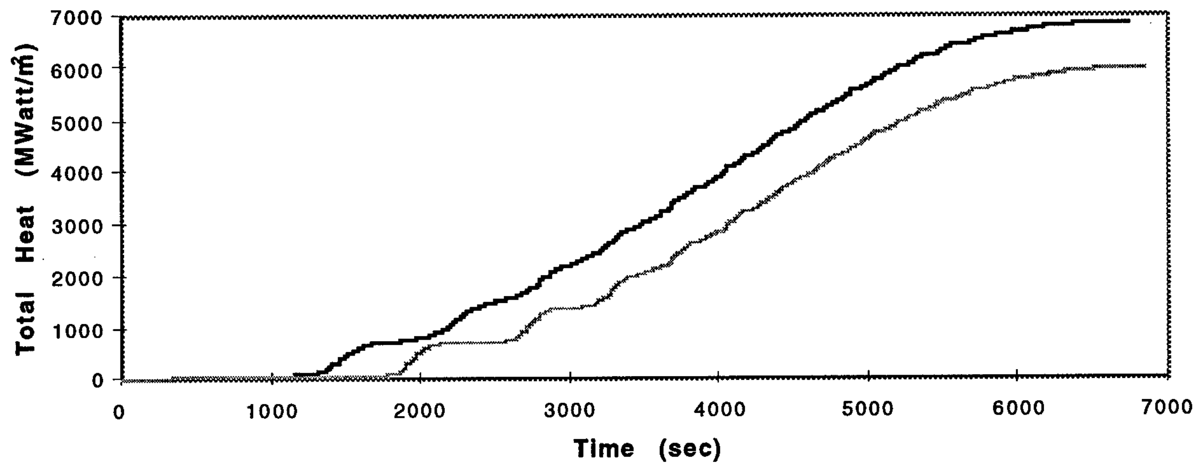

FIGURE 5. Total Heat for a Low January Flight and a High July Flight.

TABLE 2. Seasonal 90% Confidence Intervals for Peak RASV Altitude.

	January	April	July	October
Lower Altitude Limit (m)	111,749	122,856	157,935	125,711
Upper Altitude Limit (m)	149,055	162,563	202,920	166,608

TABLE 3. Seasonal 90% Confidence Intervals for Peak RASV Heat Rate (based on a 0.3048 m reference sphere).

	January	April	July	October
Lower Heat Rate Limit (kW•sec/m^2)	2427.7	2561.7	3134.8	2616.1
Upper Heat Rate Limit (kW•sec/m^2)	3170.0	3642.2	4521.8	3751.1

Substantial variations were also noted in skipping behavior. Despite the variability in peak altitude, total energy (mass*gravity*height + mass*velocity^2/2) was equal among trajectories, since high trajectories had corresponding lower velocities at apogee. Additional runs indicated that solar effects (i.e., geomagnetic storm effects) upon RASV performance are small. This was not a surprise since skips did not bottom out in the upper atmosphere on any trajectory.

SUMMARY

A sequence of 80 Monte Carlo, geographically varying atmospheres, together with flight parameters obtained from a baseline trajectory for a conceptual Boeing RASV spaceplane has indicated that around-the-world polar, skipping trajectories can be used to lift payloads of about 11,340 kg into near-orbit conditions in a variety of atmospheric cases. Such payloads would be capable of lifting satellites into low earth orbit by use of a small (e.g., to provide 1,524 m/sec of velocity change) upper stage.

Baseline flight parameters were obtained by attempting to lift the largest possible payload into the prescribed near-orbit conditions and return the spaceplane to its launch site in a 1962 U.S. Standard Atmosphere. A sled-launched, SSME powered vehicle with two-position extendable nozzles was prescribed and it was supposed that the payload was returned to earth (a worst-case condition). Some flight characteristics (peak altitude, skip amplitudes, and heat rate) displayed substantial variability due to atmospheric (including wind) variations when flight controls from the baseline case were applied. Further work is required to understand the nature of larger skipping amplitudes that occurred late in flight within certain atmospheres and to determine what constitutes an ideal skipping trajectory.

Acknowledgments

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